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Size effect tests of normal-strength and high-strength RC columns subjected to axial compressive loading

Dong Li [a], Liu Jin [a,b,*], Xiuli Du [a,*], Jia Fu [a], Aizhen Lu [a]

[a] *Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China*
[b] *Department of Civil Engineering, Tsinghua University, Beijing 100084, China*

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ABSTRACT

Geometrically similar reinforced concrete (RC) columns subjected to axial compressive loading were tested for the study of size effect. Herein the present work, a series of axial compressive tests of 43 RC columns with different sizes (in the ratio 1:2:3:4), different concrete strength grades (i.e. the average compressive strengths were 33.2 MPa for NSC and 65.8 MPa for HSC, respectively), different longitudinal (i.e. 1.5% and 2.5%) and transversal (in the volume-stirrup ratios of 0%, 0.65%, 0.94% and 1.2–1.31%) reinforcement ratios and different slenderness ratios (i.e. 3 and 4.5) were conducted. In the tests, the width of the square cross-section of the RC columns was between 200 mm and 800 mm, and the length varied from 600 mm to 2700 mm. The overall mechanical performances of the RC columns, involving the failure patterns, the nominal compressive stress–strain relationships, the peak load-carrying capacity, the nominal compressive strength, the post-peak softening behavior and the buckling and necking of steel rebar were observed and explored. From the test observations one can find that, for both the normal-strength and the high-strength RC columns, the nominal compressive strength decreased with the increase of structure size. The test observations indicated the existence of size effect. Specifically, RC columns with a higher slenderness ratio, a lower reinforcement ratio and a higher concrete strength grade presented a stronger size effect. It was concluded that the bi-logarithmic plots of nominal compressive strengths for different RC columns followed closely the "size effect law (SEL)" proposed by Bažant.

1. Introduction

Reinforced concrete (RC) has become one of the most popular construction materials and has been widely used in many types of engineering structures, most of which have very large dimensions, such as high-rise buildings, cross-sea bridges, underground and mountain tunnels, gravity and arch dams, off-shore platforms, giant nuclear power plants and protective containment of nuclear reactors. As the dimensions of these engineering structures are becoming larger and larger, the safety of these large-sized constructions, especially taking into account the use of high-strength concrete, has become one of the most concerned topics. Consequently, the need of knowledge in this field necessitates the development of accurate and reliable theories for their analysis and assessment. By general convention, the structural load capacity predicted by any deterministic strength theory (e.g. elastic, plastic or elastoplastic strength criterion) exhibits no size effect [1]. However, it is increasingly being accepted that size effect exists theoretically [2–8] and can be observed in numerous experiments conducted for plain concrete components and RC members involving beams, columns and beam–column connections [9–20].

The research on size effect of concrete structures has fallen into two major directions, (1) material size effect, and (2) component size effect.

Studies on material size effect mainly focused on the influences of aggregate size, aggregate distribution, mix proportion, concrete strength grade and crack length on the global mechanical properties, which is a complex materials science problem [10]. Steel is an elastoplastic material and pronounces no size effect. While, concrete is a heterogeneous material which is full of micro-cracks at the moment of birth. Upon loading, these micro-cracks become active and begin to propagate. A strong stress concentration would develop around the crack tip and the micro-cracks would localize into a major macro-crack which leads to the eventual failure of the structure [21]. Therefore, the size effect and the nonlinearity of global mechanical properties of concrete material are mainly caused by its heterogeneity [22]. Accordingly, this behavior of

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* Corresponding authors at: Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China. Tel.: +86 15811171018 (L. Jin), +86 13801139161 (X. Du).

E-mail addresses: kinglew2007@163.com (L. Jin), duxiuli2015@163.com (X. Du).

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concrete is characterized by post-peak strain softening which is due to progressive development of damage in the form of micro-cracks and localization of such micro-cracks into a major macro-crack that leads to the final failure [10]. These inherent features make the global mechanical properties of concrete extremely hard to be described.

For component size effect, it is a structural mechanics problem including not only the most basic material size effect, but also the size effect contributed by the influence of mutual effect between different materials. Taking RC members for example, the size effect would be caused and affected by (1) the inherent features of concrete and steel, and (2) the complex mutual effect between concrete and steel rebar. This study is primarily concerned with the size effect of RC columns. It is now clear that size effect will be encountered in all the failures of RC structures, in which the failure is initiated within the concrete rather than in the steel. Accordingly, the key points in the investigations of the size effect and the global mechanical properties of RC members contain the concrete material and the mutual effect between steel rebar and the surrounding concrete [23]. That is to say, material fracture characteristics are not the only reason why a size effect must be expected to occur in RC members. It has been realized that if the load–deflection response exhibits post-peak softening, and the softening is not due to nonlinear geometric effects (i.e. the so-called P–$\varDelta$ effect), then in general, the post-peak softening response exhibits a size effect, and so does the nominal strength [10,12,14,15]. Moreover, the mutual effect including the failure of bond (i.e. slip or separation) between concrete and steel rebar also has a strong influence on the size effect of RC members [24–30]. Simply to say, the process of softening is related to the heterogeneity of the material in the domain within the structural dimension, and the situation is further complicated when reinforcement is embedded in the structure taking into account the complex mutual effect between concrete and steel rebar [15].

All of the theoretical and experimental efforts mentioned above have contributed to the knowledge on the size effect in RC members. Size effect has also been roughly put into the currently used RC structure design codes of China [31,32]. For instance, the ratio of the compressive strengths of standard plain concrete cube samples, sized of $100 \times 100 \times 100$ mm, $150 \times 150 \times 150$ mm and $200 \times 200 \times 200$ mm, is 1.05:1:0.95. However, the size of the tested concrete components is still limited to a relatively small range (e.g. for the most concerned axially loaded RC columns in this study, the maximum cross-sectional size in [10,12,14,15] are 50.8 mm, 200 mm and 300 mm, respectively) and the size effect is extrapolated from small-sized specimens which is empirical and imprecise. Therefore, it remains unknown for the possible size effect of very large specimens. This leads to a very uncertain and unsafe design of large-sized RC structures. Moreover, most of the experimental efforts have concentrated on the size effect of RC members with normal-strength concrete (NSC) rather than with high-strength concrete (HSC) (e.g. the efforts in [11,16] just gave some size effect tests on plain HSC columns and the corresponding structural size is also limited to a relatively small range). Therefore, more practical full-size specimens, including the use of NSC and HSC, should be conducted for the investigation of size effect of RC members.

Herein this study, a series of test efforts on the global mechanical behavior of RC columns subjected to axial compressive loading were undertaken for two objectives. One was to examine the possible size effect of larger-sized normal-strength and high-strength RC columns under axial compression, and the other one was to validate the effectiveness of the available theoretical size effect laws. A total of 43 RC columns with different sizes, different concrete strength grades, different longitudinal and transverse reinforcement ratios and different slenderness ratios were designed to be geometrically similar. The width of the square cross-section of the RC columns was between 200 mm and 800 mm, and the length varied from 600 mm to 2700 mm. This should be an extension of the earlier studies [10–12,14–16], in which the component size range was about 12 mm and 300 mm. Based on the test observations, the overall mechanical performances of the RC columns were studied, and the size effect was analyzed.

After the introduction, the paper is organized as follows. Section 2 reviews the theoretical efforts on size effect based on fracture mechanics and some other principles. Section 3 introduces the details of the experiment, including the properties of concrete and steel rebar utilized, the geometric details of the RC columns and the experimental settings. Sections 4 describes the test results of the normal-strength and the high-strength RC columns under axial compression, including the corresponding failure patterns and the nominal compressive stress–strain relationships. In Section 5, further data analysis on the size effect are carried out, and the comparison of the present test results and SEL proposed by Bažant [3] are made. Finally, some concluding remarks are drawn in Section 6.

2. Review of theoretical efforts on size effect based on fracture mechanics

The nominal strength of geometrically similar structures, predicted by elastoplastic mechanics (i.e. strength criterion), is [1]

$$\sigma_{\mathrm{Nu}} = c_{\mathrm{N}} \frac{P_{\mathrm{u}}}{bD} \tag{1}$$

in which, σ_{Nu} is independent of the structure size D which exhibit no size effect (Fig. 1 – black horizontal dashed line). P_{u} is the maximum load, b is the width of the structure or specimen and c_{N} is a dimensionless constant chosen for convenience. The size effect is understood as any dependence of nominal strength and brittleness on structure size, which is a feature typical of fracture mechanics [1]. It is now widely accepted that the mathematical modeling of such behavior should be based on fracture mechanics. These kind of material models must also involve an energy quantity (called the fracture energy) or an equivalent length quantity (called the characteristic length), which is a material property. A great deal of concrete nonlinear fracture models based on fracture mechanics have been established for finite element (FE) analysis. It can be distinguished by three different kinds of fracture models for concrete, (1) cohesive models, on the basis of FE analysis, such as fictitious crack model [33] and crack band model [21]; (2) equivalent elastic crack model, on the basis of analytical analysis, such as two parameter fracture model [34], size effect model [3] and equivalent crack model [35]; (3) double-K fracture model [36–39] and double-G fracture model [40] based on a linear asymptotic superposition assumption. All of the fracture models mentioned above are widely accepted by researchers and they are able to describe the size effect of concrete by including a characteristic length of micro-structure. In addition, the constitutive models with non-local softening [41–48] are also employed in the investigation of size effect in concrete structures and great progresses have been made.

Besides, differences between 2D and 3D size effects should be of particular concern. Accordingly, a constant width b makes the specimens at two-dimensional scaling, while a proportional increased width b makes the specimens at three-dimensional scaling. In 3D models of concrete components, there is a layer, near the side walls, of constant thickness in which the crack must be nonplanar and the crack front curved (which is called the shear-lip phenomenon) [6]. It would bring about additional problems, because different portions of the specimen thickness b would be occupied by the surface layer as b varies. This could cause the average fracture energy varies with width b and create additional